

(19) World Intellectual Property  
Organization  
International Bureau



(43) International Publication Date  
11 March 2004 (11.03.2004)

PCT

(10) International Publication Number  
**WO 2004/021634 A1**

(51) International Patent Classification<sup>7</sup>: **H04L 1/06, H04B 7/005**

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(21) International Application Number:  
**PCT/US2003/026395**

(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VC, VN, YU, ZA, ZM, ZW.

(22) International Filing Date: 19 August 2003 (19.08.2003)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:  
10/229,209 27 August 2002 (27.08.2002) US

(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, RO, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

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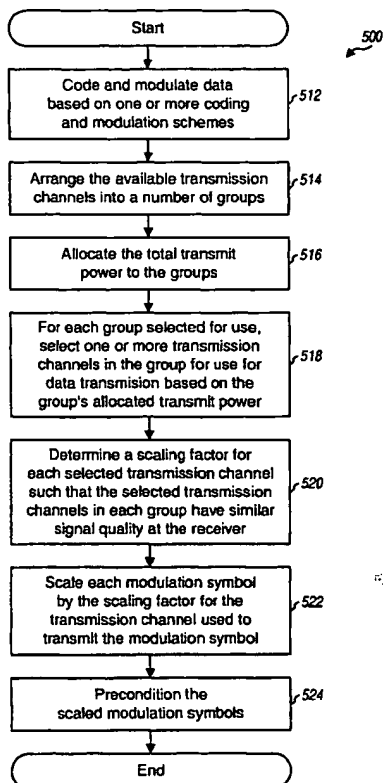
Published:

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(54) Title: **CODED MIMO SYSTEMS WITH SELECTIVE CHANNEL INVERSION APPLIED PER EIGENMODE**



(57) Abstract: Techniques to perform selective channel inversion per eigenmode in a MIMO system to achieve high spectral efficiency while reducing complexity at both the transmitter and receiver are presented. The available transmission channels are arranged into a number of groups, where each group may include all transmission channels (or frequency bins) for a respective eigenmode of a MIMO channel. The total transmit power is allocated to the groups using a particular group power allocation scheme. Selective channel inversion is then performed independently for each group selected for use for data transmission. For each such group, one or more transmission channels in the group are selected for use, and a scaling factor is determined for each selected channel such that all selected channels for the group achieve similar received signal quality (e.g., received SNR).

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## **CODED MIMO SYSTEMS WITH SELECTIVE CHANNEL INVERSION APPLIED PER EIGENMODE**

### **BACKGROUND**

#### **Field**

[1001] The present invention relates generally to data communication, and more specifically to techniques for performing selective channel inversion per eigenmode for MIMO systems.

#### **Background**

[1002] A multiple-input multiple-output (MIMO) communication system employs multiple ( $N_T$ ) transmit antennas and multiple ( $N_R$ ) receive antennas for data transmission. A MIMO channel formed by the  $N_T$  transmit and  $N_R$  receive antennas may be decomposed into  $N_S$  independent channels, with  $N_S \leq \min\{N_T, N_R\}$ . Each of the  $N_S$  independent channels is also referred to as a spatial subchannel or eigenmode of the MIMO channel.

[1003] The spatial subchannels of a wideband MIMO system may encounter different channel conditions due to various factors such as fading and multipath. Each spatial subchannel may thus experience frequency selective fading, which is characterized by different channel gains at different frequencies of the overall system bandwidth. Assuming no power control, this then results in different signal-to-noise-and-interference ratios (SNRs) at different frequencies of each spatial subchannel, which would then be able to support different data rates for a particular level of performance (e.g., 1% packet error rate).

[1004] To combat frequency selective fading in a wideband channel, orthogonal frequency division multiplexing (OFDM) may be used to effectively partition the overall system bandwidth into a number of ( $N_F$ ) subbands, which are also referred to as frequency bins or subchannels. With OFDM, each subband is associated with a respective subcarrier upon which data may be modulated. For a MIMO system that utilizes OFDM (i.e., a MIMO-OFDM system), each subband of each spatial subchannel may be viewed as an independent transmission channel.

[1005] A key challenge in a coded communication system is the selection of the appropriate data rates and coding and modulation schemes to use for a data transmission based on the channel conditions. A major goal for the system is to maximize spectral efficiency while reducing complexity for both the transmitter and receiver.

[1006] One straightforward technique for selecting data rates and coding and modulation schemes is to "bit load" each transmission channel in the system according to its transmission capability. However, this technique has several major drawbacks. First, coding and modulating individually for each transmission channel can significantly increase the complexity of the processing at both the transmitter and receiver. Second, coding individually for each transmission channel may greatly increase coding and decoding delay.

[1007] There is, therefore, a need in the art for techniques to achieve high spectral efficiency in MIMO systems without having to individually code for each transmission channel.

## SUMMARY

[1008] Techniques are provided herein to perform selective channel inversion per eigenmode in a MIMO system to achieve high spectral efficiency while reducing complexity at both the transmitter and receiver. The available transmission channels are arranged into a number of groups, where each group may include all transmission channels (or frequency bins) for an eigenmode of a MIMO channel. The total transmit power is allocated to the groups using a particular power allocation scheme (e.g., uniform power allocation, water-filling, and so on). Selective channel inversion is then performed independently for each group selected for use for data transmission (i.e., with non-zero allocated transmit power). For each such group, one or more transmission channels in the group is selected for use, and a scaling factor is determined for each selected channel such that all selected channels for the group are inverted and achieve similar received signal quality (e.g., received SNR).

[1009] Various aspects and embodiments of the invention are described in further detail below. The invention further provides methods, program codes, digital signal processors, transmitter units, receiver units, and other apparatuses and elements that

implement various aspects, embodiments, and features of the invention, as described in further detail below.

## BRIEF DESCRIPTION OF THE DRAWINGS

[1010] The features, nature, and advantages of the present invention will become more apparent from the detailed description set forth below when taken in conjunction with the drawings in which like reference characters identify correspondingly throughout and wherein:

[1011] FIG. 1 graphically illustrates eigenvalue decomposition for a MIMO-OFDM system;

[1012] FIG. 2 shows plots of the average spectral efficiency achieved by three transmission schemes for an example  $4 \times 4$  MIMO system;

[1013] FIG. 3 is a block diagram of an access point and a user terminal in the MIMO-OFDM system;

[1014] FIG. 4 is a block diagram of a transmitter unit in the access point; and

[1015] FIG. 5 is a flow diagram for processing data using selective channel inversion per eigenmode.

## DETAILED DESCRIPTION

[1016] In a MIMO communication system, such as a multiple-antenna wireless communication system, the data streams transmitted from the  $N_T$  transmit antennas interfere with each other at the receiver. One technique for combating this interference is to “diagonalize” the MIMO channel to obtain a number of independent channels.

[1017] The model for a MIMO system may be expressed as:

$$\underline{y} = \underline{H}\underline{x} + \underline{n} \quad , \quad \text{Eq (1)}$$

where  $\underline{y}$  is a vector with  $N_R$  entries,  $\{y_i\}$  for  $i \in \{1, \dots, N_R\}$ , for the symbols received by the  $N_R$  receive antennas (i.e., the “received” vector);

$\underline{x}$  is a vector with  $N_T$  entries,  $\{x_j\}$  for  $j \in \{1, \dots, N_T\}$ , for the symbols transmitted from the  $N_T$  transmit antennas (i.e., the “transmitted” vector);

$\underline{\mathbf{H}}$  is an  $(N_R \times N_T)$  channel response matrix that contains the transfer functions (i.e., complex gains) from the  $N_T$  transmit antennas to the  $N_R$  receive antennas; and

$\underline{\mathbf{n}}$  is additive white Gaussian noise (AWGN) with a mean vector of  $\underline{\mathbf{0}}$  and a covariance matrix of  $\underline{\mathbf{\Lambda}}_n = \sigma^2 \underline{\mathbf{I}}$ , where  $\underline{\mathbf{0}}$  is a vector of all zeros,  $\underline{\mathbf{I}}$  is the identity matrix with ones along the diagonal and zeros everywhere else, and  $\sigma^2$  is the noise variance.

[1018] For simplicity, a flat-fading, narrowband channel is assumed. In this case, the channel response can be represented by a constant complex value for the entire system bandwidth, and the elements of the channel response matrix  $\underline{\mathbf{H}}$  are scalars. Although the assumption of frequency non-selectivity is assumed here for simplicity, the techniques described herein may be extended for frequency selective channels.

[1019] The channel response matrix  $\underline{\mathbf{H}}$  may be diagonalized by performing eigenvalue decomposition on the correlation matrix of  $\underline{\mathbf{H}}$ , which is  $\underline{\mathbf{R}} = \underline{\mathbf{H}}^H \underline{\mathbf{H}}$ . The eigenvalue decomposition of the  $(N_T \times N_T)$  correlation matrix  $\underline{\mathbf{R}}$  may be expressed as:

$$\underline{\mathbf{R}} = \underline{\mathbf{E}} \underline{\mathbf{D}} \underline{\mathbf{E}}^H, \quad \text{Eq (2)}$$

where  $\underline{\mathbf{E}}$  is an  $(N_T \times N_T)$  unitary matrix whose columns are the eigenvectors  $\underline{\mathbf{e}}_i$  of  $\underline{\mathbf{R}}$ , for  $i \in \{1, \dots, N_T\}$ ;

$\underline{\mathbf{D}}$  is an  $(N_T \times N_T)$  diagonal matrix with entries on the diagonal corresponding to the eigenvalues of  $\underline{\mathbf{R}}$ ; and

for any matrix  $\underline{\mathbf{M}}$ ,  $\underline{\mathbf{M}}^H$  denotes the conjugate transpose of  $\underline{\mathbf{M}}$ .

A unitary matrix is denoted by the property  $\underline{\mathbf{E}}^H \underline{\mathbf{E}} = \underline{\mathbf{I}}$ .

[1020] The eigenvalue decomposition may also be performed using singular value decomposition (SVD), which is known in the art.

[1021] The diagonal matrix  $\underline{\mathbf{D}}$  contains non-negative real values along the diagonal and zeros elsewhere. These diagonal entries are referred to as the eigenvalues of the matrix  $\underline{\mathbf{R}}$  and are indicative of the power gains for the independent channels of the MIMO channel. The number of independent channels for a MIMO system with  $N_T$

transmit and  $N_R$  receive antennas is the number of non-zero eigenvalues of  $\mathbf{R}$ ,  $N_S \leq \min\{N_T, N_R\}$ . These non-zero eigenvalues are denoted as  $\{\lambda_i\}$ , for  $i = \{1, \dots, N_S\}$ .

[1022] Without taking into account power constraints for the  $N_T$  transmit antennas, the MIMO channel may be diagonalized by pre-multiplying (or “preconditioning”) a “data” vector  $\mathbf{s}$  with the unitary matrix  $\mathbf{E}$  to obtain the transmitted vector  $\mathbf{x}$ . The preconditioning at the transmitter may be expressed as:

$$\mathbf{x} = \mathbf{E}\mathbf{s} \quad \text{Eq (3)}$$

[1023] At the receiver, the received vector  $\mathbf{y}$  may be pre-multiplied (or “conditioned”) with  $\mathbf{E}^H \mathbf{H}^H$  to obtain an estimate of the data vector  $\mathbf{s}$ . The conditioning to obtain the data vector estimate  $\hat{\mathbf{s}}$  may be expressed as:

$$\begin{aligned} \hat{\mathbf{s}} &= \mathbf{E}^H \mathbf{H}^H \mathbf{y} \\ &= \mathbf{E}^H \mathbf{H}^H \mathbf{H} \mathbf{E} \mathbf{s} + \mathbf{E}^H \mathbf{H}^H \mathbf{n} \\ &= \mathbf{D} \mathbf{s} + \hat{\mathbf{n}} \end{aligned} \quad \text{Eq (4)}$$

where  $\hat{\mathbf{n}}$  is AWGN with a mean vector of  $\mathbf{0}$  and a covariance matrix of  $\mathbf{\Lambda}_{\hat{\mathbf{n}}} = \sigma^2 \mathbf{D}$ .

[1024] As shown in equation (4), the preconditioning at the transmitter and the conditioning at the receiver result in the data vector  $\mathbf{s}$  being transformed by an effective channel response represented by the matrix  $\mathbf{D}$ , as well as a scaling of the noise elements. Since  $\mathbf{D}$  is a diagonal matrix, there are effectively  $N_S$  non-interfering, parallel channels. Each of these channels has a power gain equal to the square of the corresponding eigenvalue,  $\lambda_i^2$ , and a noise power equal to  $\sigma^2 \lambda_i$  for  $i \in \{1, \dots, N_S\}$ , yielding a signal-to-noise ratio of  $\lambda_i / \sigma^2$ . Thus, the power gain of each of these channels is equal to the eigenvalue,  $\lambda_i$ , for  $i \in \{1, \dots, N_S\}$ . Parallel channel  $i$  is often referred to as eigenmode  $i$  or mode  $i$ . The diagonalization of the MIMO channel as shown in equations (3) and (4) can be achieved if the transmitter is provided with the channel response matrix  $\mathbf{H}$  or equivalent information.

[1025] The eigenvalue decomposition described above may also be performed for a wideband, frequency-selective channel. For a MIMO-OFDM system, the wideband channel is divided into  $N_F$  flat-fading, orthogonal frequency bins or subbands. The eigenvalue decomposition may then be performed independently for the channel response matrix  $\underline{\mathbf{H}}(k)$  for each frequency bin,  $k$ , to determine the  $N_S$  spatial subchannels or eigenmodes for that frequency bin. Each spatial subchannel of each frequency bin is also referred to as a “transmission” channel.

[1026] The model for a MIMO-OFDM system may be expressed as:

$$\underline{\mathbf{y}}(k) = \underline{\mathbf{H}}(k)\underline{\mathbf{x}}(k) + \underline{\mathbf{n}}(k) \quad , \text{ for } k \in \{1, \dots, N_F\}. \quad \text{Eq (5)}$$

where “ $(k)$ ” denotes the  $k$ -th frequency bin.

[1027] The eigenvalue decomposition of the correlation matrix  $\underline{\mathbf{R}}(k)$  for each frequency bin may be expressed as:

$$\underline{\mathbf{R}}(k) = \underline{\mathbf{E}}(k)\underline{\mathbf{D}}(k)\underline{\mathbf{E}}^H(k) \quad \text{Eq (6)}$$

The non-zero eigenvalues for  $\underline{\mathbf{R}}(k)$  are denoted as  $\{\lambda_i(k)\}$ , for  $i = \{1, \dots, N_S\}$  and  $k = \{1, \dots, N_F\}$ . Thus, for the MIMO-OFDM system, performing eigenmode decomposition for each of the  $N_F$  frequency bins results in  $N_S$  spatial subchannels or eigenmodes for each frequency bin, or a total of  $N_S N_F$  transmission channels.

[1028] The eigenvalues may be provided in two forms - a “sorted” form and a “random-order” form. In the sorted form, the  $N_S$  eigenvalues for each frequency bin are sorted in decreasing order so that  $\{\lambda_1(k) \geq \lambda_2(k) \geq \dots \geq \lambda_{N_S}(k)\}$ , where  $\lambda_1(k)$  is the largest eigenvalue for frequency bin  $k$  and  $\lambda_{N_S}(k)$  is the smallest eigenvalue for frequency bin  $k$ . In the random-order form, the ordering of the eigenvalues may be random and further independent of frequency. The particular form selected for use, sorted or random-ordered, influences the selection of the eigenmodes for use for data transmission and the coding and modulation scheme to be used for each selected eigenmode, as described below.

[1029] FIG. 1 graphically illustrates the eigenvalue decomposition for the MIMO-OFDM system. The set of diagonal matrices,  $\underline{\mathbf{D}}(k)$  for  $k = \{1, \dots, N_F\}$ , is shown



arranged in order along an axis 110 that represents the frequency dimension. The eigenvalues,  $\{\lambda_i(k)\}$  for  $i = \{1, \dots, N_s\}$ , of each matrix  $\underline{D}(k)$  are located along the diagonal of the matrix. Axis 112 may thus be viewed as representing the spatial dimension. The eigenmode  $i$  for all frequency bins (or simply, eigenmode  $i$ ) is associated with a set of elements,  $\{\lambda_i(k)\}$  for  $k = \{1, \dots, N_F\}$ , which is indicative of the frequency response across all  $N_F$  frequency bins for that eigenmode. The set of elements  $\{\lambda_i(k)\}$  for each eigenmode is shown by the shaded boxes along a dashed line 114. Each shaded box in FIG. 1 represents a transmission channel. For each eigenmode that experiences frequency selective fading, the elements  $\{\lambda_i(k)\}$  for that eigenmode may be different for different values of  $k$ .

[1030] If the eigenvalues in each diagonal matrix  $\underline{D}(k)$  are sorted in descending order, then eigenmode 1 (which is also referred to as the principal eigenmode) would include the largest eigenvalue,  $\lambda_1(k)$ , in each matrix, and eigenmode  $N_s$  would include the smallest eigenvalue,  $\lambda_{N_s}(k)$ , in each matrix.

[1031] The eigenvalue decomposition for each frequency bin in the MIMO-OFDM system results in a total of  $N_s N_F$  eigenvalues for the  $N_s N_F$  transmission channels over the entire bandwidth. Each transmission channel may achieve a different SNR and may be associated with different transmission capability. Various power allocation schemes (or transmission schemes) may be used to distribute the total transmit power to these transmission channels to achieve high overall spectral efficiency, which is given in units of bit/second per Hertz (bps/Hz). Some of these schemes are described in further detail below.

### 1. Water-Filling

[1032] The “water-filling” or “water-pouring” scheme may be used to optimally distribute the total transmit power across the transmission channels such that the overall spectral efficiency is maximized, under the constraint that the total transmit power at the transmitter is limited to  $P_{total}$ . The water-filling scheme distributes power over the  $N_s N_F$  transmission channels such that the channels with increasingly higher SNRs receive increasingly greater fractions of the total transmit power. The transmit power

allocated to a given transmission channel is determined by that channel's SNR, which may be given as  $\lambda_i(k)/\sigma^2$ , where  $\lambda_i(k)$  is the  $i$ -th eigenvalue in the  $k$ -th frequency bin.

[1033] The procedure for performing water-filling is known in the art and not described herein. The result of the water-filling is a specific transmit power allocation to each of the  $N_s N_F$  transmission channels, which is denoted as  $P_i(k)$ , for  $i = \{1, \dots, N_s\}$  and  $k = \{1, \dots, N_F\}$ . The power allocation is performed such that the following condition is satisfied:

$$P_{total} = \sum_{k \in K} \sum_{i \in L} P_i(k) , \quad \text{Eq (7)}$$

where  $L = \{1, \dots, N_s\}$  and  $K = \{1, \dots, N_F\}$ .

[1034] Based on the allocated transmit powers of  $P_i(k)$ , for  $i = \{1, \dots, N_s\}$  and  $k = \{1, \dots, N_F\}$ , the received SNR,  $\gamma_i(k)$ , for each transmission channel may be expressed as:

$$\gamma_i(k) = \frac{P_i(k) \lambda_i(k)}{\sigma^2} , \text{ for } i = \{1, \dots, N_s\} \text{ and } k = \{1, \dots, N_F\} . \quad \text{Eq (8)}$$

[1035] The total spectral efficiency  $C$  for the  $N_s N_F$  transmission channels may then be computed based on a continuous, monotonically increasing logarithmic function for capacity, as follows:

$$C = \sum_{k=1}^{N_F} \sum_{i=1}^{N_s} \log_2(1 + \gamma_i(k)) . \quad \text{Eq (9)}$$

[1036] In a typical communication system, the total range of received SNRs expected to be observed may be partitioned into a number of sub-ranges. Each sub-range may then be associated with a particular coding and modulation scheme chosen to yield the highest spectral efficiency for a given bit error rate (BER), frame error rate (FER), or packet error rate (PER). The water-filling power allocation may result in a different received SNR for each of the  $N_s N_F$  transmission channels. This would then result in the use of many different coding/modulation schemes for the transmission channels. The coding/modulation per transmission channel increases the overall

spectral efficiency at the expense of greater complexity for both the transmitter and receiver.

## 2. Selective Channel Inversion Applied to All Transmission Channels

[1037] The “SCI-for-all-channels” scheme performs selective channel inversion (SCI) on all transmission channels such that those selected for use achieve approximately equal received SNRs at the receiver. This would then allow a common coding and modulation scheme to be used for all selected transmission channels. This scheme greatly reduces complexity for both the transmitter and receiver in comparison to the water-filling scheme. The equalization of the received SNRs may be achieved by first selecting all or only a subset of the  $N_s N_F$  available transmission channels for use for data transmission. The channel selection may result in the elimination of poor channels with low SNRs. The total transmit power  $P_{total}$  is then distributed across the selected transmission channels in such a way that the received SNR is approximately equal for all selected transmission channels.

[1038] If “full” channel inversion is performed for all  $N_s N_F$  available transmission channels, then the total transmit power  $P_{total}$  may be allocated such that approximately equal signal power is received for all these channels. An appropriate amount of transmit power  $P_i(k)$  to allocate to eigenmode  $i$  of frequency bin  $k$  may be expressed as:

$$P_i(k) = \frac{\alpha P_{total}}{\lambda_i(k)}, \quad \text{Eq (10)}$$

where  $\alpha$  is a normalization factor used to distribute the total transmit power among the available transmission channels. This normalization factor,  $\alpha$ , may be expressed as:

$$\alpha = \frac{1}{\sum_{i \in L} \sum_{k \in K} \lambda_i(k)^{-1}}. \quad \text{Eq (11)}$$

[1039] The normalization factor,  $\alpha$ , ensures approximately equal received signal power for all transmission channels, which is given as  $\alpha P_{total}$ . The total transmit power

is thus effectively distributed (unevenly) across all available transmission channels based on their channel power gains, which is given by the eigenvalues  $\lambda_i(k)$ .

[1040] If “selective” channel inversion is performed, then only transmission channels whose received powers are at or above a particular threshold  $\beta$  relative to the total received power are selected for use for data transmission. Transmission channels whose received powers fall below this threshold are discarded and not used. For each selected transmission channel, the transmit power to be allocated to the channel is determined as described above, such that all selected transmission channels are received at approximately equal power levels. The threshold  $\beta$  may be selected to maximize spectral efficiency or based on some other criterion.

[1041] The selection of the transmission channels for use may be performed as follows. Initially, an average power gain  $P_{avg}$  is computed for all available transmission channels and may be expressed as:

$$P_{avg} = \frac{1}{N_F N_S} \sum_{k=1}^{N_F} \sum_{i=1}^{N_S} \lambda_i(k) \quad \text{Eq (12)}$$

[1042] The transmit power to allocate to each transmission channel may then be expressed as:

$$P_i(k) = \begin{cases} \frac{\tilde{\alpha} P_{total}}{\lambda_i(k)} & , \lambda_i(k) \geq \beta P_{avg} \\ 0 & , \text{otherwise} \end{cases} \quad \text{Eq (13)}$$

where  $\beta$  is the threshold and  $\tilde{\alpha}$  is a normalization factor that is similar to  $\alpha$  in equation (11). However, the normalization factor  $\tilde{\alpha}$  is computed over only the selected transmission channels and may be expressed as:

$$\tilde{\alpha} = \frac{1}{\sum_{\lambda_i(k) \geq \beta P_{avg}} \lambda_i(k)^{-1}} \quad \text{Eq (14)}$$

The threshold  $\beta$  may be derived as described below (in Section 3.2).

[1043] As shown in equation (13), a transmission channel is selected for use if its eigenvalue (or channel power gain) is greater than or equal to a power threshold (i.e.,  $\lambda_i(k) \geq \beta P_{avg}$ ). Since the normalization factor  $\tilde{\alpha}$  is computed based only on the selected transmission channels, the total transmit power  $P_{total}$  is distributed to the selected transmission channels based on their channel gains such that all selected transmission channels have approximately equal received power, which may be expressed as  $\tilde{\alpha} P_{total}$ .

[1044] The equalization of the received SNRs for all selected transmission channels can thus be achieved by non-uniform distribution of the total transmit power across these channels. The approximately equal received SNRs would then allow the use of a single data rate and a common coding/modulation scheme for all selected transmission channels, which would greatly reduce complexity.

### 3. Selective Channel Inversion Applied Per Eigenmode

[1045] The "SCI-per-eigenmode" scheme performs selective channel inversion independently for each eigenmode to provide improved performance. In an embodiment, the  $N_s N_F$  transmission channels are arranged into  $N_s$  groups such that each group includes all  $N_F$  frequency bins for a given eigenmode (i.e., group  $i$  includes the spatial subchannels for all  $N_F$  frequency bins for eigenmode  $i$ ). There is thus one group for each eigenmode.

[1046] The SCI-per-eigenmode scheme includes two steps. In the first step, the total transmit power  $P_{total}$  is distributed to the  $N_s$  groups based on a particular group power allocation scheme. In the second step, selective channel inversion is performed independently for each group to distribute that group's allocated transmit power to the  $N_F$  frequency bins in the group. Each of these steps is described in further detail below.

#### 3.1 Power Allocation Across Groups

[1047] The total transmit power  $P_{total}$  may be distributed to the  $N_s$  groups in various manners, some of which are described below.

[1048] In a first embodiment, the total transmit power  $P_{total}$  is distributed uniformly across all  $N_S$  groups such that they are all allocated equal power. The transmit power  $P_G(i)$  allocated to each group may be expressed as:

$$P_G(i) = \frac{P_{total}}{N_S}, \text{ for } i \in \{1, \dots, N_S\}. \quad \text{Eq (15)}$$

[1049] In a second embodiment, the total transmit power  $P_{total}$  is distributed to the  $N_S$  groups based on water-filling across all available transmission channels. For this embodiment, the total transmit power,  $P_{total}$ , is first distributed to all  $N_S N_F$  transmission channels using water-filling, as described above. Each transmission channel is allocated  $P_i(k)$ , for  $i \in \{1, \dots, N_S\}$  and  $k = \{1, \dots, N_F\}$ . The transmit power allocated to each group can then be determined by summing over the transmit powers allocated to the  $N_F$  transmission channels in that group. The transmit power allocated to group  $i$  may be expressed as:

$$P_G(i) = \sum_{k=1}^{N_F} P_i(k), \text{ for } i \in \{1, \dots, N_S\}. \quad \text{Eq (16)}$$

[1050] In a third embodiment, the total transmit power  $P_{total}$  is distributed to the  $N_S$  groups based on water-filling across all groups using their average channel SNRs. Initially, the average channel SNR,  $\gamma_{avg}(i)$ , for each group is determined as:

$$\gamma_{avg}(i) = \frac{1}{N_F} \sum_{k=1}^{N_F} \frac{\lambda_i(k)}{\sigma^2}, \text{ for } i \in \{1, \dots, N_S\}. \quad \text{Eq (17)}$$

Water-filling is then performed to distribute the total transmit power  $P_{total}$  across the  $N_S$  groups based on their average channel SNRs. The transmit power allocated to each of the  $N_S$  groups is denoted as  $P_G(i)$ , for  $i \in \{1, \dots, N_S\}$ .

[1051] In a fourth embodiment, the total transmit power  $P_{total}$  is distributed to the  $N_S$  groups based on water-filling across all groups using the received SNRs of the transmission channels after channel inversion. For this embodiment, the total transmit power  $P_{total}$  is first distributed uniformly to the  $N_S$  groups as shown above in equation

(15) such that each group is allocated an initial transmit power of  $\tilde{P}_G(i) = P_{total} / N_s$ , for  $i \in \{1, \dots, N_s\}$ . Selective channel inversion is then performed independently on each group to determine an initial power allocation,  $\tilde{P}_i(k)$  for  $k = \{1, \dots, N_F\}$ , for each frequency bin in the group. The received SNR,  $\tilde{\gamma}_i(k)$ , for each frequency bin is next determined based on the initial power allocation  $\tilde{P}_i(k)$ , as shown in equation (8). The average received SNR  $\tilde{\gamma}_{avg}(i)$  for each group is then computed as follows:

$$\tilde{\gamma}_{avg}(i) = \frac{1}{N_F} \sum_{k=1}^{N_F} \tilde{\gamma}_i(k) \quad , \text{ for } i \in \{1, \dots, N_s\} \quad . \quad \text{Eq (18)}$$

[1052] The total transmit power  $P_{total}$  is then distributed to the  $N_s$  groups using water-filling based on their average received SNRs,  $\tilde{\gamma}_{avg}(i)$  for  $i \in \{1, \dots, N_s\}$ . The results of the water-filling power allocation are revised (i.e., final) transmit power allocations  $P_G(i)$ , for  $i \in \{1, \dots, N_s\}$ , for the  $N_s$  groups. Selective channel inversion is again performed independently for each group to distribute the group's allocated transmit power  $P_G(i)$  to the frequency bins in the group. Each frequency bin would then be allocated transmit power  $P_i(k)$  by the second selective channel inversion.

[1053] The second selective channel inversion need not be performed for a given group if (1) the revised transmit power allocated to the group by the water-filling is greater than the initial uniform power allocation (i.e.,  $P_G(i) > \tilde{P}_G(i)$ ) and (2) all frequency bins in the group were selected for use in the initial selective channel inversion. For this specific case, the new power allocation  $P_i(k)$  for each frequency bin in the group may be expressed as:

$$P_i(k) = \frac{P_G(i)}{\tilde{P}_G(i)} \tilde{P}_i(k) \quad , \text{ for } k \in \{1, \dots, N_F\} \quad . \quad \text{Eq (19)}$$

Equation (19) may be used because (1) all frequency bins in the group have already been selected for use and no additional frequency bin can be selected even though the revised power allocation  $P_G(i)$  for the group is higher than the initial power allocation

$\tilde{P}_G(i)$ , and (2) the initial selective channel inversion already determines the proper distribution of power to the frequency bins in the group to achieve approximately equal received SNRs for these channels. In all other cases, the selective channel inversion is performed again for each group to determine the transmit power allocations,  $P_i(k)$  for  $k \in \{1, \dots, N_F\}$ , for the frequency bins in the group.

### 3.2 Selective Channel Inversion Applied to Each Group

[1054] Once the total transmit power  $P_{total}$  has been distributed to the  $N_S$  groups using any one of the group power allocation schemes described above, selective channel inversion is performed independently for each of the  $N_S$  groups and on the  $N_F$  frequency bins within each group. The selective channel inversion for each group may be performed as follows.

[1055] Initially, the average power gain,  $P_{avg}(i)$ , for each group is determined as:

$$P_{avg}(i) = \frac{1}{N_F} \sum_{k=1}^{N_F} \lambda_i(k) \quad , \text{ for } i \in \{1, \dots, N_S\} . \quad \text{Eq (20)}$$

The transmit power allocated to frequency bin  $k$  in group  $i$  may then be expressed as:

$$P_i(k) = \begin{cases} \frac{\tilde{\alpha}_i P_{total}}{\lambda_i(k)} & , \lambda_i(k) \geq \beta_i P_{avg}(i) \\ 0 & , \text{ otherwise } , \end{cases} \quad \text{Eq (21)}$$

where  $\beta_i$  is the threshold and  $\tilde{\alpha}_i$  is the normalization factor for group  $i$ . The normalization factor  $\tilde{\alpha}_i$  for each group is computed over only the selected transmission channels for that group, and may be expressed as:

$$\tilde{\alpha}_i = \frac{1}{\sum_{\lambda_i(k) \geq \beta_i P_{avg}(i)} \lambda_i(k)^{-1}} . \quad \text{Eq (22)}$$

The summation of the inverse channel power gains in equation (22) takes into account the channel power gains over all selected frequency bins of group  $i$ .



[1056] The threshold  $\beta_i$  to select frequency bins for use in each group may be set based on various criteria, e.g., to optimize spectral efficiency. In one embodiment, the threshold  $\beta_i$  is set based on the channel power gains (or eigenvalues) and the spectral efficiencies of the selected frequency bins based on uniform transmit power allocation across the frequency bins in each group, as described below.

[1057] For this embodiment, the derivation of the threshold  $\beta_i$  for group  $i$  proceeds as follows (where the derivation is performed independently for each group). Initially, the eigenvalues for all  $N_F$  frequency bins in the group are ranked and placed in a list  $G_i(\lambda)$ , for  $\lambda \in \{1, \dots, N_F\}$ , in descending order such that  $G_i(1) = \max\{\lambda_i(k)\}$  and  $G_i(N_F) = \min\{\lambda_i(k)\}$  for  $i \in \{1, \dots, N_S\}$ .

[1058] For each  $\lambda$ , where  $\lambda \in \{1, \dots, N_F\}$ , the spectral efficiency for the  $\lambda$  best frequency bins is computed, where "best" refers to the frequency bins with the highest power gains,  $G_i(\lambda)$ . This can be achieved as follows. First, the total transmit power available to the group,  $P_G(i)$ , is distributed to the  $\lambda$  best frequency bins using any one of the power allocation schemes described above. For simplicity, the uniform power allocation scheme is used, and the transmit power for each of the  $\lambda$  frequency bins is  $P_G(i)/\lambda$ . Next, the received SNR for each of the  $\lambda$  frequency bins is computed as:

$$\gamma_i^\lambda(j) = \frac{P_G(i)G_i(j)}{\sigma^2\lambda}, \text{ for } j \in \{1, \dots, \lambda\}. \quad \text{Eq (23)}$$

[1059] The spectral efficiency  $C_i(\lambda)$  for the  $\lambda$  best frequency bins in group  $i$  is then computed as:

$$C_i(\lambda) = \rho \sum_{j=1}^{\lambda} \log_2(1 + \gamma_i^\lambda(j)), \quad \text{Eq (24)}$$

where  $\rho$  is a scale factor used to account for inefficiencies in the coding and modulation scheme selected for use.

[1060] The spectral efficiency  $C_i(\lambda)$  is computed for each value of  $\lambda$ , where  $\lambda \in \{1, \dots, N_F\}$ , and stored in an array. After all  $N_F$  values of  $C_i(\lambda)$  have been computed for the  $N_F$  possible combinations of selected frequency bins, the array of spectral

efficiencies is traversed and the largest value of  $C_i(\lambda)$  is determined. The value of  $\lambda$ ,  $\lambda_{\max}$ , corresponding to the largest  $C_i(\lambda)$  is then the number of frequency bins that results in the maximum spectral efficiency for the channel conditions being evaluated and using uniform transmit power allocation.

[1061] Since the eigenvalues for the  $N_F$  frequency bins in group  $i$  are ranked in decreasing order in the list  $G_i(\lambda)$ , the spectral efficiency increases as more frequency bins are selected for use until the optimal point is reached, after which the spectral efficiency decreases because more of the group's transmit power is allocated to poorer frequency bins. Thus, instead of computing the spectral efficiency  $C_i(\lambda)$  for all possible values of  $\lambda$ , the spectral efficiency  $C_i(\lambda)$  for each new value of  $\lambda$  may be compared against the spectral efficiency  $C_i(\lambda-1)$  for the previous value of  $\lambda$ . The computation may then be terminated if the optimal spectral efficiency is reached, which is indicated by  $C_i(\lambda) < C_i(\lambda-1)$ .

[1062] The threshold  $\beta_i$  may then be expressed as:

$$\beta_i = \frac{G_i(\lambda_{\max})}{P_{\text{avg}}(i)}, \quad \text{Eq (25)}$$

where  $P_{\text{avg}}(i)$  is determined as shown in equation (20).

[1063] The threshold  $\beta_i$  may also be set based on some other criterion or some other power allocation scheme (instead of uniform allocation).

[1064] Selective channel inversion is described in further detail in U.S. Patent Application Serial No. 09/860,274, filed May 17, 2001, Serial No. 09/881,610, filed June 14, 2001, and Serial No. 09/892,379, filed June 26, 2001, all three entitled "Method and Apparatus for Processing Data for Transmission in a Multi-Channel Communication System Using Selective Channel Inversion," assigned to the assignee of the present application and incorporated herein by reference.

[1065] Performing selective channel inversion independently for each group results in a set of transmit power allocations,  $P_i(k)$  for  $k \in \{1, \dots, N_F\}$ , for the  $N_F$  frequency bins in each group. The selective channel inversion may result in less than  $N_F$  frequency bins being selected for use for any given group. The unselected frequency

bins would be allocated no transmit power (i.e.,  $P_i(k) = 0$  for these bins). The power allocations for the selected frequency bins are such that these bins achieve approximately equal received SNRs. This then allows a single data rate and a common coding/modulation scheme to be used for all selected frequency bins in each group.

[1066] For the sorted form, the eigenvalues  $\lambda_i(k)$ , for  $i \in \{1, \dots, N_s\}$ , for each diagonal matrix  $\underline{D}(k)$  are sorted such that the diagonal elements with smaller indices are generally larger. Eigenmode 1 would then be associated with the largest eigenvalue in each of the  $N_F$  diagonal matrices, eigenmode 2 would be associated with the second largest eigenvalue, and so on. For the sorted form, even though the channel inversion is performed over all  $N_F$  frequency bins for each eigenmode, the eigenmodes with lower indices are not likely to have too many bad frequency bins (if any) and excessive transmit power is not used for bad bins.

[1067] If water-filling is used to distribute the total transmit power to the  $N_s$  eigenmodes, then the number of eigenmodes selected for use may be reduced at low SNRs. The sorted form thus has the advantage that at low SNRs, the coding and modulation are further simplified through the reduction in the number of eigenmodes selected for use.

[1068] For the random-ordered form, the eigenvalues for each diagonal matrix  $\underline{D}(k)$  are randomly ordered. This may result in a smaller variation in the average received SNRs for all of the eigenmodes. In this case, fewer than  $N_s$  common coding and modulation schemes may be used for the  $N_s$  eigenmodes.

[1069] In one transmission scheme, if a group is to be used for data transmission, then all  $N_F$  frequency bins in that group are selected (i.e., any active eigenmode needs to be a complete eigenmode). The frequency selective nature of an eigenmode can be exaggerated if one or more frequency bins are omitted from use. This greater frequency selective fading can cause higher level of inter-symbol interference (ISI), which is a phenomenon whereby each symbol in a received signal acts as distortion to subsequent symbols in the received signal. Equalization may then be required at the receiver to mitigate the deleterious effects of ISI distortion. This equalization may be avoided by performing full channel inversion on all frequency bins of each eigenmode that is selected for use. This transmission scheme may be advantageously used in conjunction

with the sorted form and the water-filling power allocation since, as noted above, the eigenmodes with lower indices are not likely to have too many bad frequency bins.

[1070] FIG. 2 shows plots of the average spectral efficiency achieved by three transmission schemes for an example  $4 \times 4$  MIMO system with total transmit power of  $P_{total} = 4$ . Three plots are shown in FIG. 2 for three transmission schemes: (1) water-filling power allocation over all transmission channels, (2) selective channel inversion applied to all transmission channels (SCI-for-all-channels), and (3) selective channel inversion applied to each eigenmode independently (SCI-per-eigenmode) with the total transmit power being distributed among the four groups using water-filling based on their average channel SNRs.

[1071] The average spectral efficiency is plotted versus operating SNR, which is defined as  $\gamma_{op} = 1/\sigma^2$ . FIG. 2 indicates that the water-filling power allocation (plot 210) yields the highest spectral efficiency, as expected. The performance of the SCI-for-all-channels scheme (plot 230) is approximately 2.5 dB worse than that of the optimal water-filling scheme at a spectral efficiency of 15 bps/Hz. However, the SCI-for-all channels scheme results in much lower complexity for both the transmitter and receiver since a single data rate and a common coding/modulation scheme may be used for all selected transmission channels. The performance of the SCI-per-eigenmode scheme (plot 220) is approximately 1.5 dB worse than that of the water-filling scheme and 1.0 dB better than that of the SCI-for-all-channels scheme at 15 bps/Hz spectral efficiency. This result is expected since the SCI-per-eigenmode scheme combines water-filling with selective channel inversion. Although the SCI-per-eigenmode scheme is more complex than the SCI-for-all-channels scheme, it is less complex than the water-filling scheme and achieves comparable performance.

[1072] FIG. 3 is a block diagram of an embodiment of an access point 310 and a user terminal 350 in a MIMO-OFDM system 300.

[1073] At access point 310, traffic data (i.e., information bits) from a data source 312 is provided to a transmit (TX) data processor 314, which codes, interleaves, and modulates the data to provide modulation symbols. A TX MIMO processor 320 further processes the modulation symbols to provide preconditioned symbols, which are then multiplexed with pilot data and provided to  $N_T$  modulators (MOD) 322a through 322t, one for each transmit antenna. Each modulator 322 processes a respective stream of

preconditioned symbols to generate a modulated signal, which is then transmitted via a respective antenna 324.

[1074] At user terminal 350, the modulated signals transmitted from the  $N_T$  antennas 324a through 324t are received by  $N_R$  antennas 352a through 352r. The received signal from each antenna 352 is provided to a respective demodulator (DEMOD) 354. Each demodulator 354 conditions (e.g., filters, amplifies, and frequency downconverts) and digitizes the received signal to provide a stream of samples, and further processes the samples to provide a stream of received symbols. An RX MIMO processor 360 then processes the  $N_R$  received symbol streams to provide  $N_T$  streams of recovered symbols, which are estimates of the modulation symbols sent by the access point.

[1075] The processing for the reverse path from the user terminal to the access point may be similar to, or different from, the processing for the forward path. The reverse path may be used to send channel state information (CSI) from the user terminal back to the access point. The CSI is used at the access point to select the proper coding and modulation schemes for use and to perform the selective channel inversion.

[1076] Controllers 330 and 370 direct the operation at the access point and user terminal, respectively. Memories 332 and 372 provide storage for program codes and data used by controllers 330 and 370, respectively.

[1077] FIG. 4 is a block diagram of an embodiment of a transmitter unit 400, which is an embodiment of the transmitter portion of access point 310 in FIG. 3. Transmitter unit 400 may also be used for user terminal 350.

[1078] Within TX data processor 314, an encoder/puncturer 412 receives and codes the traffic data (i.e., the information bits) in accordance with one or more coding schemes to provide coded bits. A channel interleaver 414 then interleaves the coded bits based on one or more interleaving schemes to provide a combination of time, spatial, and/or frequency diversity. A symbol mapping element 416 then maps the interleaved data in accordance with one or more modulation schemes (e.g., QPSK, M-PSK, M-QAM, and so on) to provide modulation symbols.

[1079] The coding and modulation for the  $N_S$  groups may be performed in various manners. In one embodiment, a separate coding and modulation scheme is used for each group of transmission channels for which selective channel inversion is applied. For this embodiment, a separate set of encoder, interleaver, and symbol mapping

element may be used for each group. In another embodiment, a common coding scheme is used for all groups, followed by a variable-rate puncturer and a separate modulation scheme for each group. This embodiment reduces hardware complexity at both the transmitter and the receiver. In other embodiments, trellis coding and Turbo coding may also be used to code the information bits.

[1080] Within TX MIMO processor 320, estimates of the impulse response of the MIMO channel are provided to a fast Fourier transform (FFT) unit 422 as a sequence of matrices of time-domain samples,  $\hat{\underline{H}}(n)$ . FFT unit 422 then performs an FFT on each set of  $N_F$  matrices  $\hat{\underline{H}}(n)$  to provide a corresponding set of  $N_F$  estimated channel frequency response matrices,  $\hat{\underline{H}}(k)$  for  $k \in \{1, \dots, N_F\}$ .

[1081] A unit 424 then performs eigenvalue decomposition on each matrix  $\hat{\underline{H}}(k)$  to provide the unitary matrix  $\underline{E}(k)$  and the diagonal matrix  $\underline{D}(k)$ , as described above. The diagonal matrices  $\underline{D}(k)$  are provided to a power allocation unit 430 and the unitary matrices  $\underline{E}(k)$  are provided to a spatial processor 450.

[1082] Power allocation unit 430 distributes the total transmit power  $P_{total}$  to the  $N_S$  groups using any one of the group power allocation schemes described above. This results in power allocations of  $P_G(i)$ , for  $i \in \{1, \dots, N_S\}$ , for the  $N_S$  groups. Unit 430 then performs selective channel inversion independently for each group based on that group's allocated transmit power  $P_G(i)$ . This results in power allocations of  $P_i(k)$ , for  $k \in \{1, \dots, N_F\}$ , for the  $N_F$  frequency bins in each group, where  $P_i(k)$  may be equal to zero for one or more bins in the group (if it is not required that any active eigenmode be complete eigenmode). Unit 432 performs water-filling to distribute the total transmit power, and unit 434 performs selective channel inversion for each group. The power allocations  $P_i(k)$  for all transmission channels are provided to a signal scaling unit 440.

[1083] Unit 440 receives and scales the modulation symbols based on the power allocations to provide scaled modulation symbols. The signal scaling for each modulation symbol may be expressed as:

$$s'_i(k) = s_i(k) \sqrt{P_i(k)} \quad , \text{ for } i \in \{1, \dots, N_S\} \text{ and } k \in \{1, \dots, N_F\} \quad , \quad \text{Eq (26)}$$

where  $s_i(k)$  is the modulation symbol to be transmitted on eigenmode  $i$  of frequency bin  $k$ ,  $s'_i(k)$  is the corresponding scaled modulation symbol, and  $\sqrt{P_i(k)}$  is the scaling factor for this symbol to achieve the channel inversion.

[1084] A spatial processor 450 then preconditions the scaled modulation symbols based on the unitary matrices  $\underline{E}(k)$  to provide preconditioned symbols, as follows:

$$\underline{x}(k) = \underline{E}(k)\underline{\tilde{s}}(k) \quad , \quad \text{for } k \in \{1, \dots, N_F\} \quad , \quad \text{Eq (27)}$$

where  $\underline{\tilde{s}}(k) = [s_1(k) \ s_2(k) \ \dots \ s_{N_T}(k)]^T$ ,  $\underline{x}(k) = [x_1(k) \ x_2(k) \ \dots \ x_{N_T}(k)]^T$ , and  $x_i(k)$  is the preconditioned symbol to be sent on frequency bin  $k$  of transmit antenna  $i$ . If  $N_s < N_T$ , then  $\underline{\tilde{s}}(k)$  would include  $N_s$  non-zero entries and the remaining  $N_T - N_s$  entries would be zero.

[1085] A multiplexer (MUX) 452 receives and multiplexes pilot data with the preconditioned symbols. The pilot data may be transmitted on all or a subset of the transmission channels, and is used at the receiver to estimate the MIMO channel. Multiplexer 452 provides one stream of preconditioned symbols to each OFDM modulator 322.

[1086] Within each OFDM modulator 322, an IFFT unit receives the preconditioned symbol stream and performs an inverse FFT on each set of  $N_F$  symbols for the  $N_F$  frequency bins to obtain a corresponding time-domain representation, which is referred to as an OFDM symbol. For each OFDM symbol, a cyclic prefix generator repeats a portion of the OFDM symbol to form a corresponding transmission symbol. The cyclic prefix ensures that the transmission symbol retains its orthogonal properties in the presence of multipath delay spread. A transmitter unit then converts the transmission symbols into one or more analog signals and further conditions (e.g., amplifies, filters, and frequency upconverts) the analog signals to generate a modulated signal that is then transmitted from the associated antenna 324.

[1087] FIG. 5 is a flow diagram of an embodiment of a process 500 for processing data using selective channel inversion per eigenmode. Initially, data to be transmitted is coded and modulated based on one or more coding and modulation schemes (step 512).

[1088] The available transmission channels are arranged into a number of groups, where each group may include all frequency bins for a given eigenmode (step 514).

(Each group may also be defined to include frequency bins for multiple eigenmodes, or only a subset of the frequency bins for a single eigenmode.) The total transmit power is then allocated to the groups using a particular group power allocation scheme (step 516).

[1089] Selective channel inversion is then performed independently for each group. For each group selected for use (i.e., with non-zero allocated transmit power), one or more frequency bins in the group is selected for use for data transmission based on the transmit power allocated to the group (step 518). Alternatively, all frequency bins in the group may be selected if the group is to be used. A scaling factor is then determined for each selected frequency bin such that all selected frequency bins for each group have similar received signal quality, which may be quantified by received SNR, received power, or some other measure (step 520).

[1090] Each modulation symbol is then scaled by the scaling factor for the frequency bin to be used to transmit that modulation symbol (step 522). The scaled modulation symbols may further be preconditioned to diagonalize the MIMO channel (step 524). The preconditioned symbols are further processed and transmitted.

[1091] For clarity, specific embodiments have been described above. Variations to these embodiments and other embodiments may also be derived based on the teachings described herein. For example, it is not necessary to use the SCI-per-eigenmode scheme with spatial processing (i.e., preconditioning) at the transmitter. Other techniques may also be used to diagonalize the MIMO channel without performing preconditioning at the transmitter. Some such techniques are described in U.S. Patent Application Serial No. 09/993,087, entitled "Multiple-Access Multiple-Input Multiple-Output (MIMO) Communication System," filed November 6, 2001, assigned to the assignee of the present application and incorporated herein by reference. If spatial processing is not performed at the transmitter, then the selective channel inversion may be applied per transmit antenna or some other group unit.

[1092] The selective channel inversion may be performed at the transmitter based on the estimated channel response matrix  $\hat{\mathbf{H}}(k)$ , as described above. The selective channel inversion may also be performed at the receiver based on the channel gains, the received SNRs, or some other measure of received signal quality. In any case, the transmitter is provided with sufficient channel state information (CSI), in whatever



form, such that it is able to determine (1) the particular data rate and coding and modulation scheme to use for each eigenmode and (2) the transmit power (or scaling factor) to use for each selected transmission channel such that the channels in each group have similar signal quality at the receiver (i.e., to invert the selected transmission channels).

[1093] The techniques described herein may also be used to perform selective channel inversion on groups that are defined to be something other than single eigenmode. For example, a group may be defined to include the frequency bins for multiple eigenmodes, or only some of the frequency bins for one or more eigenmodes, and so on.

[1094] For clarity, the techniques for performing selective channel inversion per eigenmode have been described specifically for a MIMO-OFDM system. These techniques may also be used for a MIMO system that does not employ OFDM. Moreover, although certain embodiments have been specifically described for the forward link, these techniques may also be applied for the reverse link.

[1095] The techniques described herein may be implemented by various means. For example, these techniques may be implemented in hardware, software, or a combination thereof. For a hardware implementation, the elements used to implement any one or a combination of the techniques may be implemented within one or more application specific integrated circuits (ASICs), digital signal processors (DSPs), digital signal processing devices (DSPDs), programmable logic devices (PLDs), field programmable gate arrays (FPGAs), processors, controllers, micro-controllers, microprocessors, other electronic units designed to perform the functions described herein, or a combination thereof.

[1096] For a software implementation, the techniques described herein may be implemented with modules (e.g., procedures, functions, and so on) that perform the functions described herein. The software codes may be stored in a memory unit (e.g., memory 332 or 372 in FIG. 3) and executed by a processor (e.g., controller 330 or 370). The memory unit may be implemented within the processor or external to the processor, in which case it can be communicatively coupled to the processor via various means as is known in the art.

[1097] Headings are included herein for reference and to aid in locating certain sections. These headings are not intended to limit the scope of the concepts described therein under, and these concepts may have applicability in other sections throughout the entire specification.

[1098] The previous description of the disclosed embodiments is provided to enable any person skilled in the art to make or use the present invention. Various modifications to these embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other embodiments without departing from the spirit or scope of the invention. Thus, the present invention is not intended to be limited to the embodiments shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

[1099] **WHAT IS CLAIMED IS:**

## CLAIMS

1. A method for processing data for transmission in a multiple-input, multiple-output (MIMO) communication system, comprising:  
arranging a plurality of available transmission channels into a plurality of groups; and  
for each group of transmission channels to be used for data transmission,  
selecting one or more transmission channels in the group for use, and  
determining a scaling factor for each selected transmission channel such that the one or more selected transmission channels in each group have similar received signal quality.
2. The method of claim 1, wherein each group includes all transmission channels corresponding to a particular eigenmode of a MIMO channel.
3. The method of claim 1, further comprising:  
allocating total transmit power to the plurality of groups, and wherein the one or more scaling factors for the one or more selected transmission channels in each group are determined based in part on the transmit power allocated to the group.
4. The method of claim 3, wherein the total transmit power is uniformly allocated to the plurality of groups.
5. The method of claim 3, wherein the total transmit power is allocated to the plurality of groups based on water-filling.
6. The method of claim 5, wherein the water-filling is performed across the plurality of available transmission channels, and wherein the transmit power allocated to each group is based on transmit powers allocated to the plurality of transmission channels in the group.

7. The method of claim 5, wherein the water-filling is performed based on average signal-to-noise-and-interference ratios (SNRs) for the plurality of groups.

8. The method of claim 5, wherein the water-filling is performed based on signal-to-noise-and-interference ratios (SNRs) for the plurality of available transmission channels after channel inversion.

9. The method of claim 1, wherein if a group is to be used for data transmission then all transmission channels in the group are selected for use.

10. The method of claim 1, further comprising:  
coding and modulating data based on one or more coding and modulation schemes to provide modulation symbols; and  
scaling each modulation symbol based on the scaling factor for the transmission channel used to transmit the modulation symbol.

11. The method of claim 10, wherein the data for each group of transmission channels is coded based on a separate coding scheme.

12. The method of claim 10, wherein the data for all groups of transmission channels is coded based on a common coding scheme, and wherein coded data for each group is punctured with a rate selected for the group.

13. The method of claim 10, further comprising:  
preconditioning scaled modulation symbols.

14. The method of claim 1, wherein the MIMO system implements orthogonal frequency division multiplexing (OFDM).

15. A method for processing data for transmission in a multiple-input, multiple-output (MIMO) communication system that implements orthogonal frequency division multiplexing (OFDM), comprising:

arranging a plurality of available transmission channels into a plurality of groups, wherein each group includes all transmission channels corresponding to a particular eigenmode of a MIMO channel;

allocating total transmit power to the plurality of groups; and

for each group of transmission channels to be used for data transmission,

selecting one or more transmission channels in the group for use, and

determining a scaling factor for each selected transmission channel,

based in part on the transmit power allocated to the group, such that the one or more selected transmission channels in each group have similar received signal quality.

16. A transmitter unit in a multiple-input, multiple-output (MIMO) communication system, comprising:

a TX data processor operative to code and modulate data based on one or more coding and modulation schemes to provide modulation symbols; and

a TX MIMO processor operative to select one or more transmission channels in each of a plurality of groups of transmission channels for use for data transmission, determine a scaling factor for each selected transmission channel such that the one or more selected transmission channels in each group have similar received signal quality, and scale each modulation symbol based on the scaling factor for the transmission channel used to transmit the modulation symbol.

17. The transmitter unit of claim 16, wherein the TX MIMO processor is further operative to allocate total transmit power to the plurality of groups, and wherein the one or more scaling factors for the one or more selected transmission channels in each group is determined based in part on the transmit power allocated to the group.

18. A transmitter unit in a multiple-input, multiple-output (MIMO) communication system that implements orthogonal frequency division multiplexing (OFDM), comprising:

a TX data processor operative to code and modulate data based on one or more coding and modulation schemes to provide modulation symbols; and

a TX MIMO processor operative to

allocate total transmit power to a plurality of groups of transmission channels, wherein each group includes all transmission channels corresponding to a particular eigenmode of a MIMO channel,

select one or more transmission channels in each group for use for data transmission,

determine a scaling factor for each selected transmission channel such that the one or more selected transmission channels in each group have similar received signal quality, and

scale each modulation symbol based on the scaling factor for the transmission channel used to transmit the modulation symbol.

19. The transmitter unit of claim 18, wherein the TX MIMO processor is further operative to precondition scaled modulation symbols.

20. An apparatus in a multiple-input, multiple-output (MIMO) communication system, comprising:

means for arranging a plurality of available transmission channels into a plurality of groups;

means for selecting one or more transmission channels in each group for use for data transmission; and

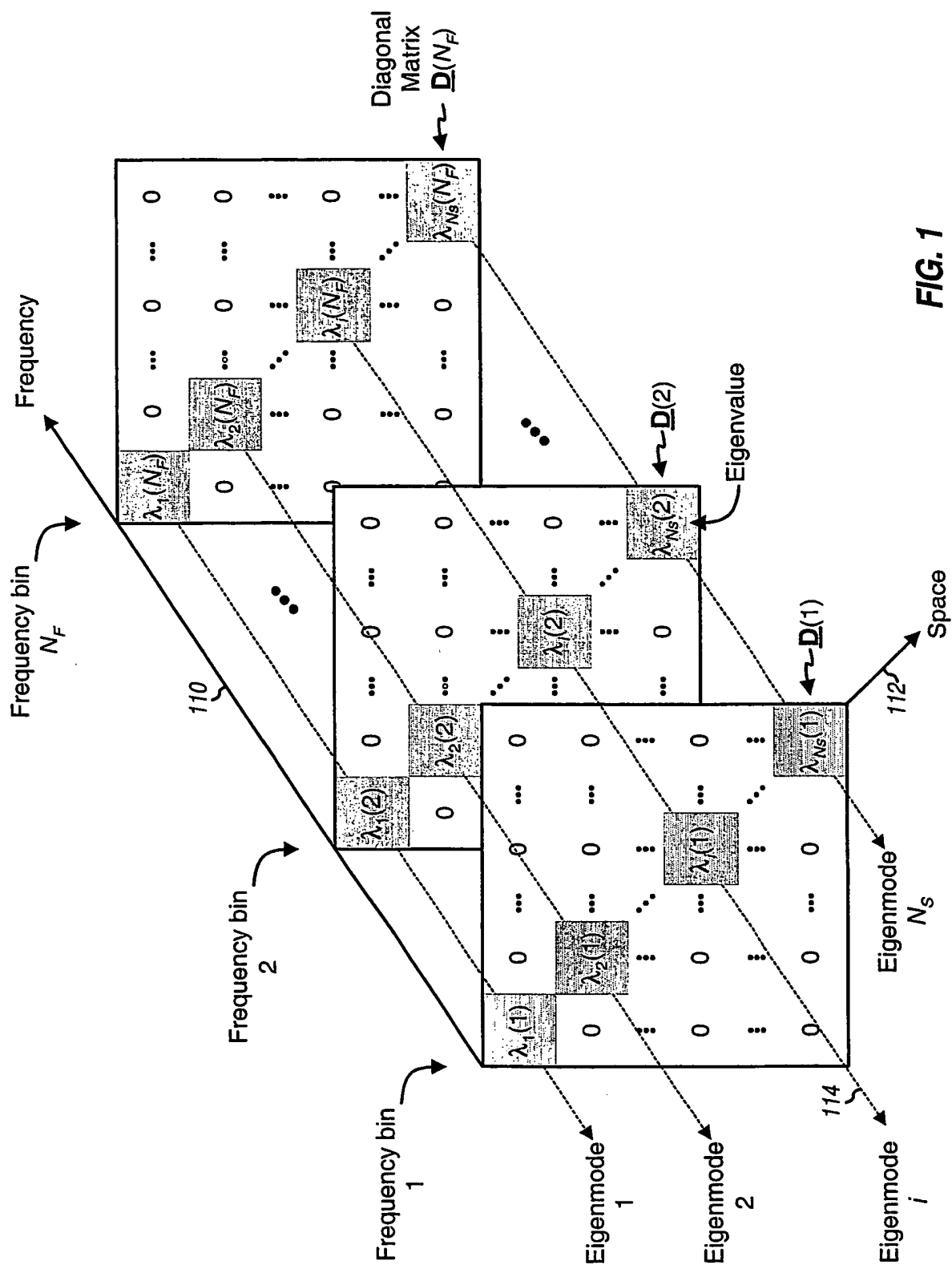
means for determining a scaling factor for each selected transmission channel such that the one or more selected transmission channels in each group have similar received signal quality.

21. The apparatus of claim 20, further comprising:

means for coding and modulating data based on one or more coding and modulation schemes to provide modulation symbols; and

means for scaling each modulation symbol based on the scaling factor for the transmission channel used to transmit the modulation symbol.

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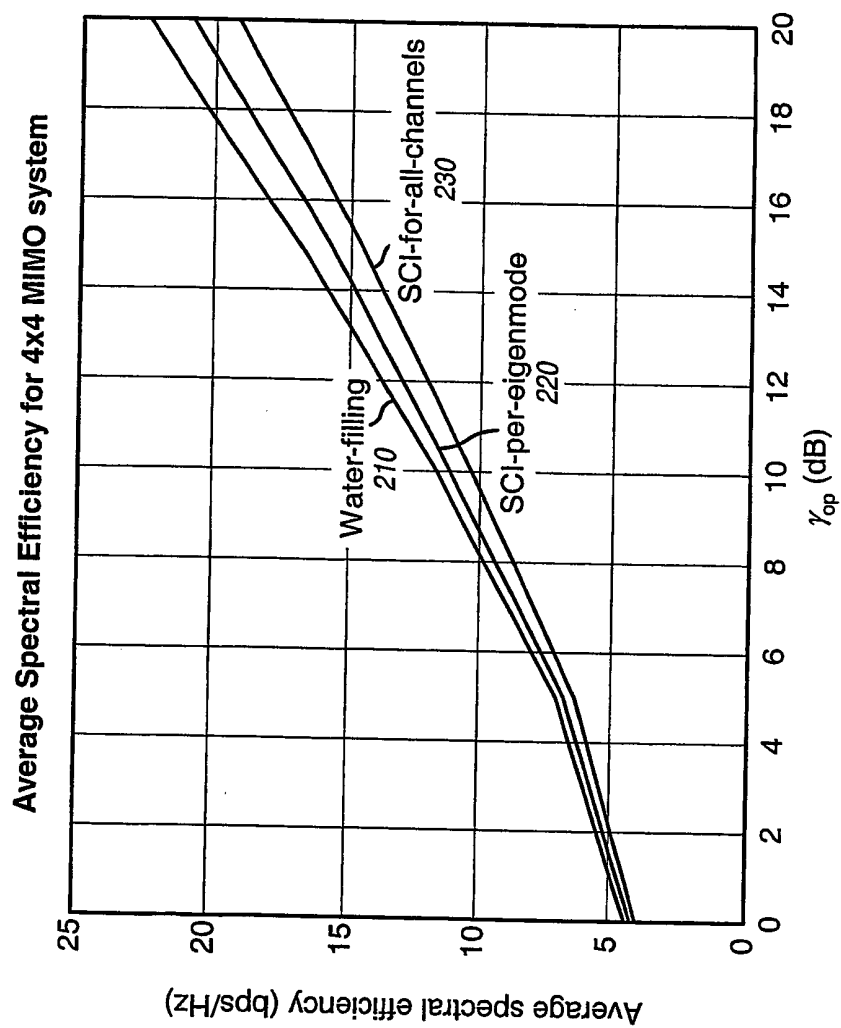


FIG. 2



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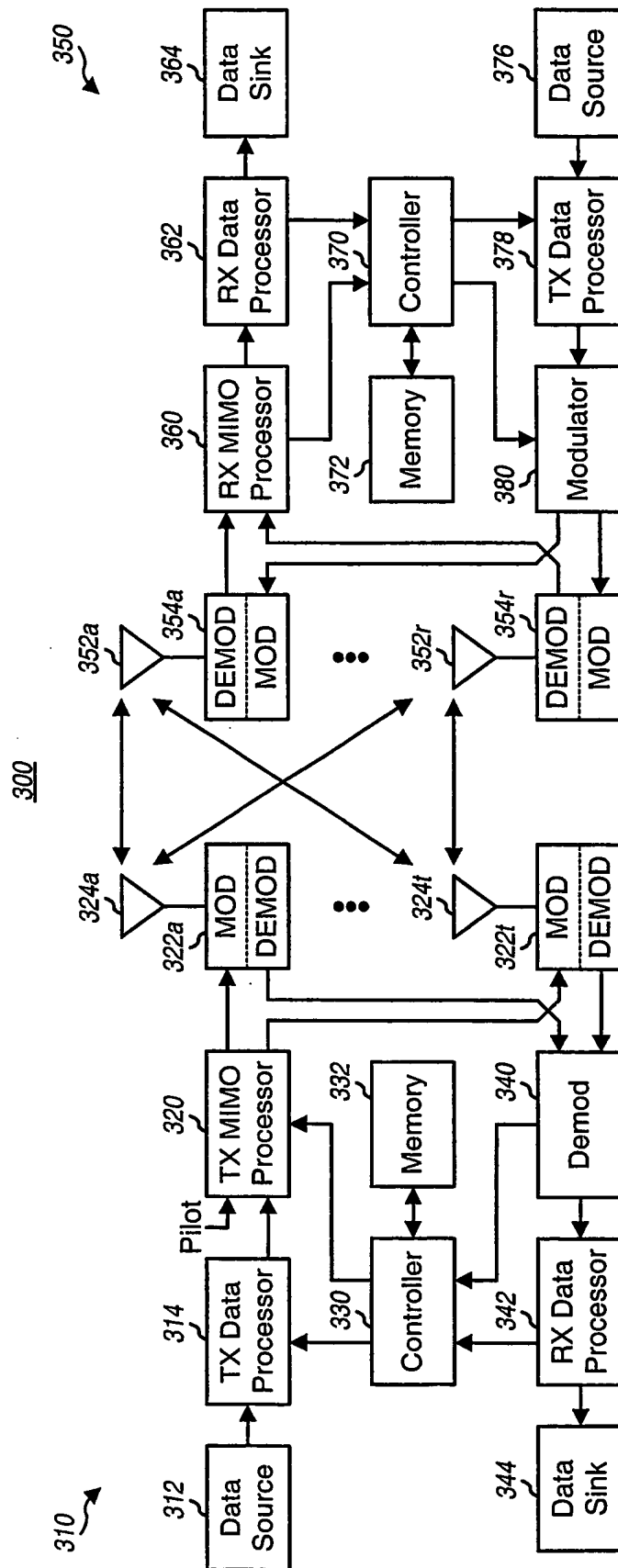


FIG. 3

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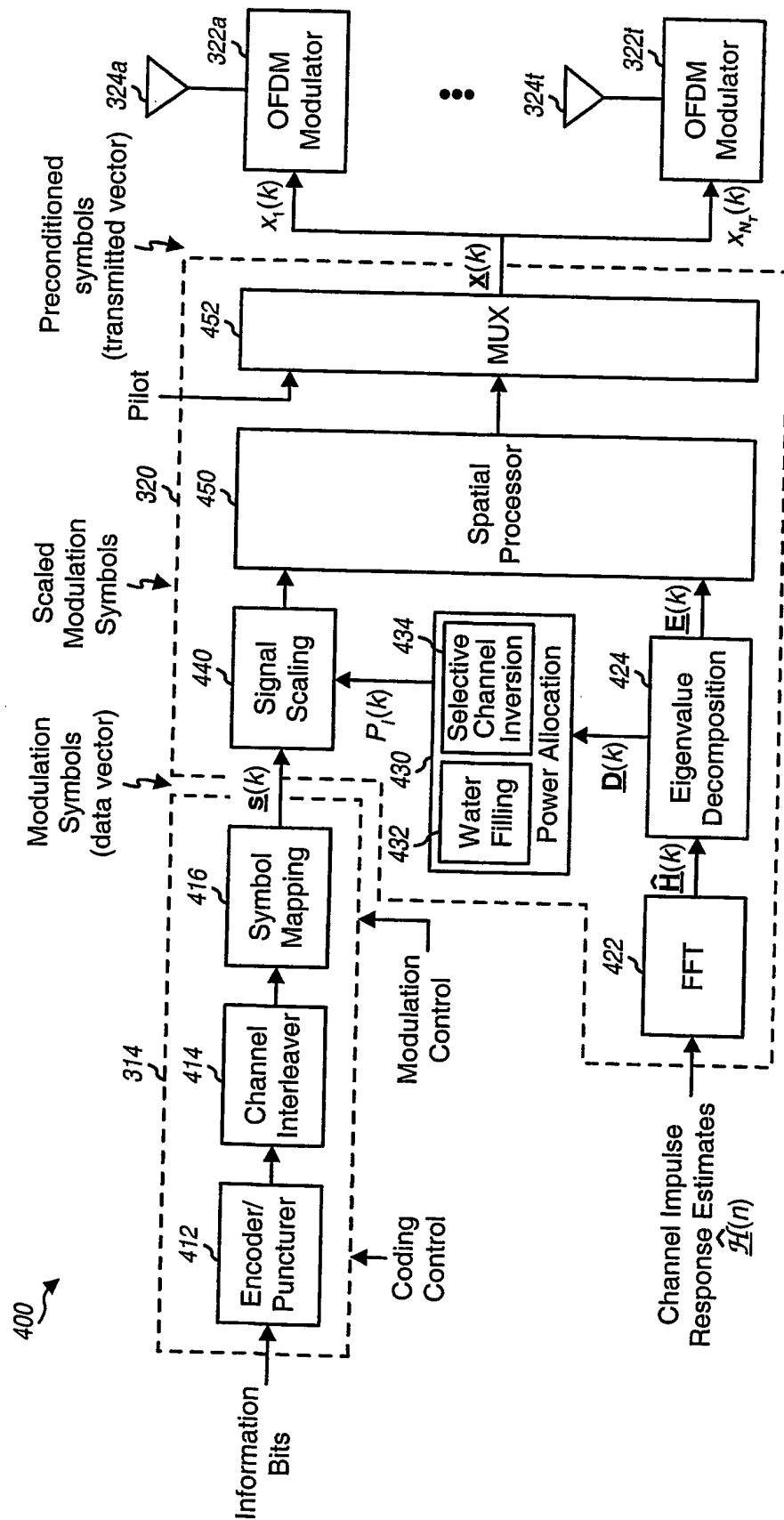
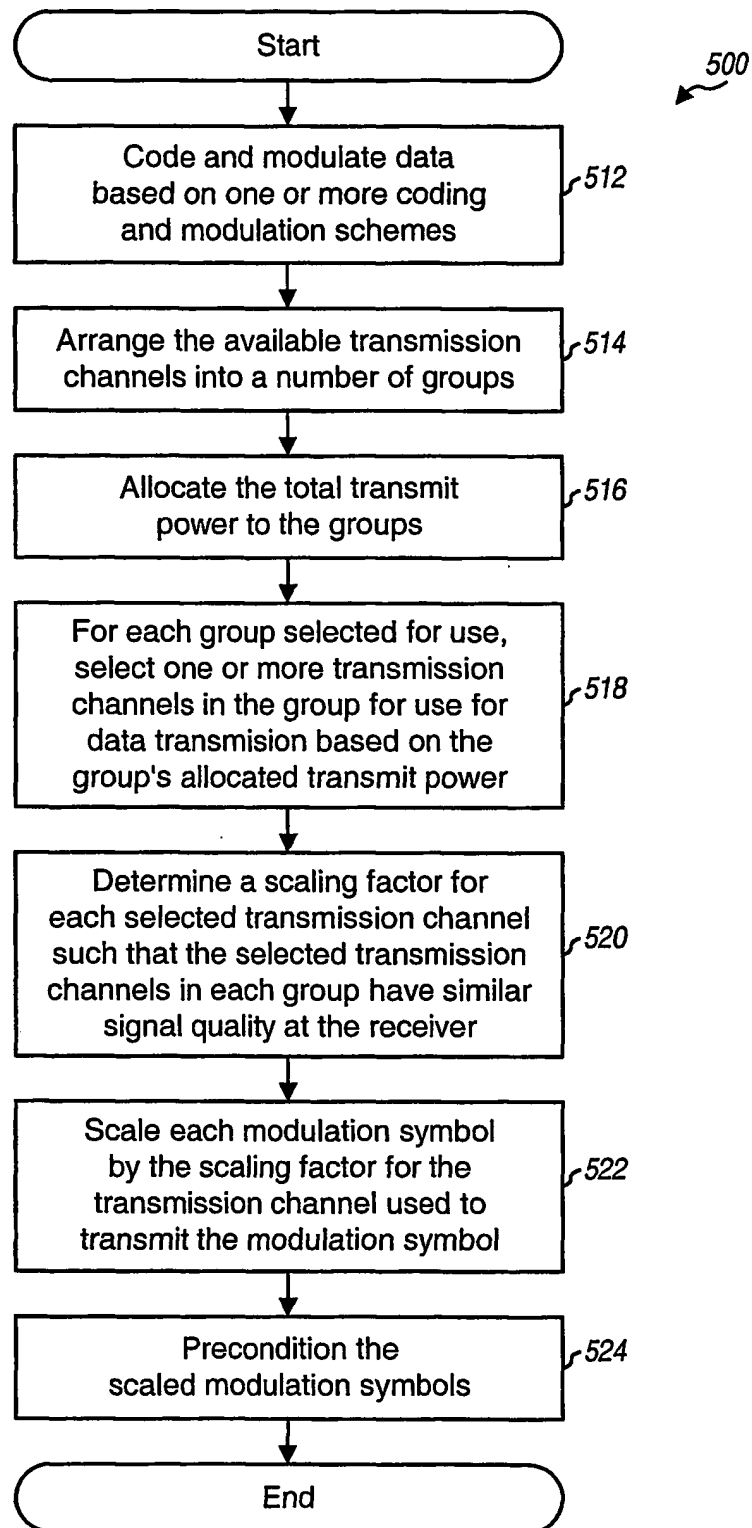


FIG. 4

**5/5****FIG. 5**

# INTERNATIONAL SEARCH REPORT

International Application No

PCT/JP 03/26395

A. CLASSIFICATION OF SUBJECT MATTER  
IPC 7 H04L1/06 H04B7/005

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)  
IPC 7 H04L H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)  
EPO-Internal, WPI Data

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X	US 2003/112880 A1 (KETCHUM JOHN W ET AL) 19 June 2003 (2003-06-19)  * abstract * page 1, right-hand column, paragraph 1 - paragraph 5 page 3, left-hand column, paragraph 2 -page 4, left-hand column, paragraph 2 page 11, right-hand column, paragraph 4 -page 12, left-hand column, paragraph 3 figure 4	1, 3, 4, 9-14, 16, 17, 20, 21
A	EP 1 117 197 A (LUCENT TECHNOLOGIES INC) 18 July 2001 (2001-07-18) * abstract * column 1, line 27 -column 2, line 2 column 6, line 15 - line 58 figures 1,3	1, 15, 16, 18, 20

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

12 December 2003

Date of mailing of the international search report

19/12/2003

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## INTERNATIONAL SEARCH REPORT

International Application No

PCT, JJ 03/26395

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P,A	<p>MIYASHITA K ET AL: "High data-rate transmission with eigenbeam-space division multiplexing (E-SDM) in a MIMO channel" VTC 2002-FALL. 2002 IEEE 56TH. VEHICULAR TECHNOLOGY CONFERENCE PROCEEDINGS. VANCOUVER, CANADA, SEPT. 24 - 28, 2002, IEEE VEHICULAR TECHNOLOGY CONFERENCE, NEW YORK, NY: IEEE, US, vol. 1 OF 4. CONF. 56, 24 September 2002 (2002-09-24), pages 1302-1306, XP010608639 ISBN: 0-7803-7467-3</p> <p>page 1302, right-hand column, paragraph 2</p> <p>page 1303, right-hand column, paragraph 3</p> <p>-left-hand column, paragraph 5</p> <p>---</p>	1,15,16, 18,20
A	<p>EP 1 185 001 A (NORTEL NETWORKS LTD) 6 March 2002 (2002-03-06)</p> <p>* abstract *</p> <p>page 3, line 30 -page 4, line 2</p> <p>---</p> <p>-/--</p>	1,15,16, 18,20

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International Application No  
PCT/US 93/26395

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Form PCT/ISA/210 (continuation of second sheet) (July 1992)

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